WL-TR-97-3080

CONCEPTUAL DEVELOPMENT OF AN ADVANCED CYCLE BARE BASE ENVIRONMENTAL CONTROL UNIT
VOLUME 1 - MAIN TEXT

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NOVEMBER 1995

FINAL DRAFT REPORT FOR 10/01/93 - 10/31/95

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
November 1995

3. REPORT TYPE AND DATES COVERED
FINAL 10/01/93 - 10/31/95

4. TITLE AND SUBTITLE
CONCEPTUAL DEVELOPMENT OF AN ADVANCED CYCLE BARE BASE ENVIRONMENTAL CONTROL UNIT
VOL 1 - MAIN TEXT

5. FUNDING NUMBERS
C: F08635-93-C-0018
PE: 6.2
PR:
TA:
WU

6. AUTHOR(S)
W. GRAEBEL, C. MOIOLA, R. BOEHM

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NEVADA ENGINEERING RESEARCH & DEVELOPMENT SYSTEMS
6452 EAST VIEWPOINT DRIVE
LAS VEGAS, NV 89115

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
FLIGHT DYNAMICS DIRECTORATE
WRIGHT LABORATORY
AIR FORCE MATERIAL COMMAND
TYNDALL AFB FLORIDA 32403-5323
POC: Kevin Grosskopf, WL/FIVCF, 904-283-3732

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
WL-TR-97-3080

11. SUPPLEMENTARY NOTES
Additional information see WL-TR-97-3081

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The objective of the present concept study was to critically review and assess innovative advanced technology concepts of heating and cooling which can be applied to ECUs to support the Global Reach-Global Power strategy of today's USAF mission while protecting the environment. Nine innovative technologies were reviewed and of these, six were rejected as unsuitable to Air Force ECU needs at the present time. Of the remaining three, Stirling cycle heat pump technology was selected as the most suited to Air Force advanced needs. Hybrid Stirling systems such as the "pulse-tube" have been identified as being capable to meet all major performance criteria such as appreciable reductions in both weight and volume, increased energy efficiency, and the elimination of occupationally hazardous or environmentally suspect refrigerants. Gains in these areas within follow-on R&D efforts will provide forward deployed forces a more capable, less logistically taxing ECU system.

14. SUBJECT TERMS
AIR FORCE, ENVIRONMNETAL CONTROL UNIT (ECU), ENERGY EFFICIENCY, POWER FACTOR, OZONE DEPLETING CHEMICAL, HEAT TRANSFER

15. NUMBER OF PAGES
41

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

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PREFACE

This report was prepared by Nevada Engineering Research & Development Systems, 6452 East Viewpoint Drive Las Vegas, Nevada 89115-7052 under contract F08635-93-C-0018, Tyndall AFB, FL 32403-5323.

The report summarizes work performed between 24 September, 1993 and 24 September 1995. Mr Kevin R. Grosskopf was the WL/FIVCF Project Manager.

EXECUTIVE SUMMARY

The Air Force is in the process of developing a new family of portable shelters for use in a wartime environment. A new generation of environmental control units (ECUs) is required to support these shelters. A lightweight, compact 5-ton field deployable heat pump using off-the-shelf technology and R-134a as the refrigerant is currently being developed as an interim substitute for the existing A/E32C-39 ECU presently used by the Air Force for Bare Base and other deployed applications. The A/E32C-39 ECU uses R-22, an HCFC, as the refrigerant. HCFCs are known suspects for ozone-depleting potential. The object of the off-the-shelf technology effort is to develop a Bare Base ECU with less weight, less volume, greater capacity, and greater operating efficiency than the A/E32C-39 using a non-ozone-depleting potential (ODP) and non-global-warming potential (GWP) refrigerant.

The technical objective of the present concept study is to critically review and assess innovative advanced technology concepts of heating and cooling which can be applied to ECUs to support the Global Reach-Global Power strategy of today's USAF mission while protecting the environment. Nine innovative technologies were reviewed. Of these, six were rejected as being unsuited to Air Force ECU needs at the present time. Of the remaining three, Stirling cycle heat pump technology was selected as being the most suited to Air Force advanced needs at this time. Thermoelectric and solid-vapor (complex compound) absorption heat pumps were alternate possibilities, ranked in that order.

1. INTRODUCTION.

1.1 Background.

The Air Force is in the process of developing a new family of portable shelters for use in a wartime environment. A new generation of environmental control units (ECUs) are required to support these units. The conventional technology presently used to meet shelter cooling loads is the vapor compression Rankine thermodynamic cycle. Current ECU capacity requirements range from 5 to 20 tons of cooling and 60,000 BTUs of heating. A lightweight, compact 5-ton field deployable heat pump using off-the-shelf technology and R-134a as the refrigerant is currently being developed as an interim substitute for the existing A/E32C-39 ECU presently used by the Air Force for Bare Base and other deployed applications. The A/E32C-39 ECU uses R-22, an HCFC, as the refrigerant. HCFCs are known suspects for ozone-depleting potential. The object of the off-the-shelf technology effort is to develop a Bare Base ECU with less weight, less volume, greater capacity, and greater operating efficiency than the A/E32C-39, and with no ozone-depleting potential (ODP) or global warming potential (GWP).

The technical objective of the present concept study is to critically review and assess innovative advanced technology concepts of heating and cooling which can be applied to ECUs to support the Global Reach-Global Power strategy of today's USAF mission while protecting the environment. Existing technologies employ chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) as refrigerants. These refrigerants have been deemed harmful to the environment, contributing to the destruction of the ozone layer and to global warming. The US is a signatory to the Montreal Protocol and under Title VI of Clean Air Act Amendments of 1990, US production of CFCs is rapidly coming to a halt, and the phase-out of HCFCs has been accelerated to occur before the original mandate year 2030. Western Europe has adopted a similar rate of phase-out with HFCs (e.g., R-32, R-125), their blends and mixtures being the replacements most used .

R-134a, an HFC, does not contain chlorine and therefore has been considered to be safe as regards ozone depletion. However R-134a is not compatible with present mineral-based refrigerant oils and lubricants, and requires extensive enhancement, resizing, and redesign of evaporators, condensers, valves, and connecting lines. Since R-134a does contribute to global warming, and since questions have been raised concerning the effect of fluorines on the ozone layer and on the toxicity of R-134a, in the US it is being regarded as a short-term replacement for the CFCs until a better technology can be found.

The goal of the current study then is to find which of the innovative technology concepts are environmentally clean (free of refrigerants which could potentially contribute to ozone layer depletion, global warming, or any other environmentally hazardous condition), and are scientifically mature and sufficiently developed to the point that the concept can be realized in a production model within a reasonable time frame of less than a decade. The advanced ECU must be sufficiently compact, light, and durable so as to be field transportable to a wartime environment after long term storage. It must be reliable and easy to maintain, with low noise emission and a minimum heat signature so as to minimize detection by hostile forces.

1.2 Scope of the Investigation.

Several of the technologies which were studied have been in the research/development stage for several decades or more, some in fact for more than a century or so, while others are fairly new and less widely tested and discussed. In reviewing the various technologies, technical literature and conference proceedings were reviewed as a means of determining the level of engineering activity as well as its progress. Because of the commercial potential which these new technologies have in the heating/refrigeration/air conditioning field, these publications sometimes omit crucial details of developments if such revelation could give competitors an unintended advantage. Also, it has been the practice of the industry to state coefficients of performance (COPs) and efficiencies at operating conditions different than that of interest to the Air Force, the operating conditions for room air conditioning usually being selected at 95°F (35°C). Under the severe operating conditions under which the Air Force ECUs would be used, COPs and operating efficiencies could be greatly reduced from anticipated values, resulting in greatly increased energy demands and less-than-desired heating and cooling. To better understand as many facets of the technology status as possible, attendance at technical meetings and discussions with engineers working in the technologies were also used in evaluation.

As a supplement to the literature study, computer models illustrating the primary features and design parameters of the most promising new technologies were developed to enable an investigation on the various physical parameters of the technology, their criticality, and their effect on meeting the requirements of the Air Force. The models were based on data obtained from the literature and data base surveys. All computer models resulting from this contract were delivered to the Air Force as a part of this report.

1.3 System Requirements.

Specific system requirements of the ECUs include the following items:

<u>Climate Conditions</u>. Advanced ECUs are required to operate in ambient conditions ranging from -25 °F (-32 °C) to 130 °F (54.5 °C), providing an internal portable shelter temperature of 72 °F ± 5 °F (22 °C ± 2.8 °C) while maintaining acceptable humidity conditions in a broad range of climate conditions.

Power Requirements. The advanced ECUs must be capable of operating from foreign and domestic commercial power supplies as well as field deployable generators. The power factor must be 0.95 nominal (+15%, -0%).

Heating and Cooling Capacity. Technologies will be selected which can be utilized over the range of heating and cooling capacities (60,000 BTUs for heating and 5 to 20 tons of cooling).

Chemical/Biological Capabilities. All technologies will be assessed as to their capability of being sealed against chemical/biological agents.

Filter-Blower Compatibility. Many of the innovative technologies mate with conventional heat exchangers, filters, and blowers presently used for heating/cooling. However, some of the technologies deviate from present standard practice, in that higher temperatures require enhanced heat transport. All technologies are assessed as to their compatibility with standard Department of Defense filter-blower assemblies, and recommendations for replacement filter-blower designs are made as needed..

Resistance to Deterioration. Assessment is made of the potential of making new technologies inert to potential chemical solvents and contaminants, as well as biological agents. Potential leakage of the medium used for the refrigerant is assessed, along with its corrosive properties. Assessment is made of the capability of the advanced ECU of being easily serviced and decontaminated should such contamination occur.

Transportability. Assessment is made of the size and weight of the advanced ECUs to insure that they can be transported at a minimum of 12 to a single 463L pallet. Transportation should be possible by all modes of air, sea, and land transport. The effect of structural loads and variations in atmospheric pressure imposed during the various modes of transportation is assessed as to its effect on structural integrity and possible leakage of refrigerant.

Weight. The presently used 5 ton A/E32C-39 ECU weighs 960 pounds. The interim replacement R-134a ECU is projected to weigh 760 pounds. The 5-ton advanced ECU should weigh less than 760 pounds.

Long-term Storage. Assessment is made of a new technology's ability to withstand long-term (20 year) storage with no degradation of performance and minimum inspection and maintenance. The corrosiveness of the chemicals contained within the ECU and their susceptibility to leakage is assessed to insure that required maintenance during the storage period should be no more than minor field-level maintenance.

Field Assembly. Assessment was made of the advanced ECUs ability to be erectable, operable, maintainable, and repairable within 0.5 man hours during all types of conventional warfare environments by military personnel with limited training on the system. This was done by assessing the ability to construct the ECU in a single compact package with a minimum of connections to auxiliary sources.

Efficiency. It is desired that the advanced ECU have a minimum cooling COP of 3.0 when the ambient outside temperature is 95°F (35°C). It should require less than 2,000 watts of electrical power to produce 12,000 BTUs of cooling.

1.4 Advanced Heat Pump Technologies Considered

The heat pump types studied under this contract included nine innovative technologies, indicated in the following list. Those technologies marked with an asterisk were also simulated with a computer model.

*1. Acoustic Heat Pumps.
*2. Brayton Cycle Heat Pumps.
3. Liquid-vapor Sorption Heat Pumps.
4. Magnetic Heat Pumps.
5. Malone-Stirling Heat Pumps.
*6. Solid-Vapor Sorption Heat Pumps.
*7. Stirling Cycle Heat Pumps.
*8. Thermoelectric Heat Pumps.
9. Vortex Tube (Ranque-Hilsch Tube) Heat Pumps.

For reference and comparison purposes vapor compression heat pumps using the conventional Rankine cycle were also studied and modeled using as refrigerants the conventional CFCs, R-134a, and ammonia.

1.5 Tradeoff Analysis.

After compilation of the data, the heat pump technologies investigated were comparatively evaluated. Technical efficiencies, operating performance, long-term storage effects, nearness-to-manufacturability, need for special supporting equipment, air transportability, durability, and environmental and occupational safety characteristics were all included in the methodology. Risk factors were assigned to the various ECU technologies by personnel at Tyndall AFB. The risk and cost drivers of each technology were assessed to the best possible degree based on best engineering judgement reached after careful assessment of the technology from the literature as well as from computer models. A probability of successful development of the technology in the sense of producing an ECU meeting Air Force requirements within a 5 year time span was arrived at. Comparison to and compatibility with the existing A/E32C-39 ECU was assessed.

Based on the results of the tradeoff analysis, three of the new heat pump technologies are recommended for potential research and development as a field deployable advanced ECU. The recommendations are graded as to desirability. A conceptual design for each of the selected technologies is indicated, engineering analyses were performed to optimize the performance characteristics of each conceptual design, and possible sources for the conduction of further research, development, and realization of the design are recommended.

It is appropriate to point out that conventional vapor-compression heating-cooling technology has been developed over a period of more than 70 years, with a gradual refinement and improvement of the devices over that period. Even so, heat pumps in the sizes considered here have not been a major portion of the market since in most localities they cannot compete economically with a combination of gas heating and vapor-compression cooling. For the performance of a new innovative technology to exceed the old, or to perhaps even come close to the old, will take a shorter but still extended time frame. The fact that most of the technologies considered here have their roots in the early nineteenth century and have not been able to compete successfully with vapor compression until environmental concerns have been raised points this out forcefully.

2. TECHNOLOGIES FOUND UNSUITED FOR AIR FORCE ECU

2.1 Unsuitable Technologies.

A detailed discussion of each of the nine technologies is contained in Volume 2, Appendices. A discussion of the use of the computer programs developed under the contract and used in assessing these technologies is given in Appendix K. Of the nine technologies reviewed under this contract, six were eliminated as not being suitable at this time and received only limited computer modelling. A discussion follows summarizing the reasons for rejection of these technologies. It should be pointed out that these technologies do have relevant areas of application, but at this time they do not seem to be appropriate for consideration as an ECU.

2.1.1 Acoustic Heat Pumps.

Acoustic heat pumps grew out of a series of theoretical studies carried out sporadically over more than a century. Their technology was furthered in the 1980's by a group at Los Alamos National Laboratories, resulting in several demonstration units and a device which was utilized on a satellite. The principle of these heat pumps is the following. A plate is placed within a tube containing a pressurized gas. An internal acoustic field is generated within the tube by a loudspeaker. Gas viscosity slows the gas velocity near the surface of the plate so that net work is done by the acoustic field and a temperature gradient is thereby established along the plate. By proper placement of heat exchangers at either ends of the plate heat pumping is accomplished. The diameter of the tube is typically around two inches or so, and the overall length of the device about 30 to 40 inches. Air can be used as the gas, but the thermodynamic properties of either helium or hydrogen give better performance.

Typical heat pumping of a device as described is about 6 watts or so, therefore the number of such tubes needed results in a bulky device. Over time helium or hydrogen will leak through most metal cylinder walls, so plating of the walls is necessary, and gas replacement pumping is necessary. Conversion of electric energy to the needed acoustic field is generally a low efficiency process, generally with conversion efficiencies ranging from 3% for ordinary loudspeakers to 50% for specially designed drivers. The heat pumping power depends on the acoustic field power, meaning that the needed input electrical power will be large. The heat exchangers must be very small, yet very efficient. The various individual tubes will have to be connected by fluid-filled heat transfer loops, increasing weight and size of the heat pumps. The theory to date has been idealized, and adequate information on design of the plates and heat exchangers does not yet exist. Overall, the power output of the device per unit volume it occupies would appear to be too low to be of use as an ECU.

2.1.2 Brayton Cycle Heat Pumps.

The reversed Brayton cycle was used as long ago as 150 years to cool yellow fever patients in Florida, and today is used in most jet airplanes where there is an abundance of compressor capability which can be used to compress air at little cost in overall efficiency. Air is typically used as the refrigerant so it is environmentally acceptable. Typically an open cycle is used in heat pumping. Air is taken in, compressed, then expanded though a turbine and returned into the room to obtain the desired cooling. An external blower is needed to cool the air between the compressor and turbine. During heating the hot air from the blower would be released into the room and the cooled air would be dumped to the outside.

Refrigeration efficiency is generally low compared to other cycles used in heat pumps, so unless a compressor is available at little extra energy cost this cycle is seldom used as a heat pump. The presence of both a turbine and a compressor increases possible maintenance and storage problems, makes decontamination very difficult, and doubles needed replacement parts.

2.1.3 Liquid-Vapor Sorption Heat Pumps.

Liquid-vapor sorption heat pumps are an old technology with low COPs which is used for applications suited to its particular restrictions. The conventional heat pumps using this technology employ either water and lithium bromide (used in nuclear submarines), or water and ammonia. The lithium bromide-water combination is subject to freezing, and would not meet the ECU storagability requirement. Ammonia-water has less of a problem since the water always contains a certain percentage of ammonia, thereby having a lowered freezing point. While ammonia is irritating at low concentrations and toxic at higher ones, the amount of ammonia involved in one heat pump would not be large, and since it would be housed outdoors and ammonia is lighter than air, fumes would rapidly dissipate. Ammonia does attack copper, brass, some plastics, and some sealing and gasketing materials.

These heat pumps are basically heat driven, so to improve the inherent low apparent efficiency of these thermally driven heat pumps conceivably waste heat from electrical generators could be used, or they could be powered by direct combustion of the fuel used to drive the generators. More directly, electrical resistance heaters could convert electrical energy to heat energy. To enhance COP these heat pumps typically use regenerators which are gravity powered and must be kept vertical. This means that the heat pump must be at least 4 feet high. Storage could not be safely done in sites with extreme ranges of annual temperature, and the potential of sloshing and/or spilling liquid in the internal chambers could pose problems during transportation. The heat exchangers needed would of necessity be bulky, and the entire device would be cumbersome and time-consuming to install.

2.1.4 Magnetic Heat Pumps.

Magnetic heat pumps operate on the principle that many magnetic materials become warmer in the presence of a magnetic field, and cooler when the field is removed. Several laboratory embodiments of this principle have been realized, including one by NASA Lewis Center scientists, where a motor was utilized to raise and lower a magnetic material in a magnetic field. For ECU use superconducting magnets with field strengths of 4 to 5 torr at ambient temperatures are needed as conventional magnets in this range are weight and volume prohibitive. While system efficiencies are difficult to determine from accounts given, the principle appears to be most efficient at temperatures near absolute zero. Both efficiencies and heat pumping capacities are substantially reduced as temperatures near room temperature are reached. Ideal efficiencies in the temperature range desired for an ECU at best appear to lie within the efficiency range of more established technologies such as the Ericsson and Brayton cycles. There appears to be little advantage to further consideration of this technology for an ECU.

2.1.5 Malone-Stirling Heat Pumps.

Around 1930 an engineer in England, J. F. J. Malone, suggested that rather than using a thermodynamic cycle where gas is compressed and phase changes occur, a cycle such as the Stirling cycle could be used with a liquid as the refrigerant, with no phase changes. Malone's original experiments used water as the refrigerant. The advent of World War II interrupted Malone's work, and it was not resumed until taken up by G. Swift at Los Alamos Laboratories in the late 1970's. Malone's original work is difficult to evaluate, since he did little analysis and nothing to quantify his demonstration experiments. Swift has provided some analysis and did construct an experimental engine. He was able to generate heat fluxes of 1.3 kilowatts at cylinder pressures of 838 psia. It does not appear that anyone has constructed a refrigerator, although that technology appears to be possible.

The extremely high pressures needed would require substantial cylinder walls and connections, and even the tiniest breach of the device would result in a high velocity stream of liquid which could cut through anything - and anyone - in its way. While water is a possible refrigerant, better performance in a more useful temperature range would be obtained through the use of more exotic liquids which are less environmentally benign and more toxic.

It appears that in the capacities required for the ECU this technology would result in a heavy, bulky device which would pose a severe potential hazard to operators and passers-by. This technology, still inadequately developed, may well have potential in some capacities and special situations, but does not appear suited to ECU needs.

2.1.6 Vortex Tube (Ranque-Hilsch Tube) Heat Pumps.

A vortex tube consists of a round tube, usually no more than an inch or so in diameter, into which high pressure compressed air is injected in such a manner as to introduce a swirling motion of the air within the tube. The swirling motion acts to compress the air, thereby heating the air near the outer wall of the tube and cooling the air at the center core of the flow. A valve on the hot end sends the inner (cool) core of air back to the other end where it emerges as cold air. Since air is the only gas used it is completely environmentally benign, and since there are no moving mechanical parts maintenance is minimal. Filters and traps must however be used to remove any moisture, oil, and dirt from the incoming air.

Vortex tubes are used to cool or heat small parts during machining, to cool small equipment enclosures, and have been used to cool humans encased in special suits. Their most critical disadvantage which rules them out of further consideration as an ECU is that to produce the desired cooling/heating capacities they would consume enormous quantities of high pressure compressed air. Because of the low efficiencies of the necessary compressors the power consumption would be much beyond the capabilities of the normal electric generators used at a Bare Base. The weights, sizes, and electrical consumption of the entire system could not conceivably meet the required ECU goals, or even come near them.

3. RECOMMENDED TECHNOLOGIES

3.1 Discussion of Acceptable Heat Pump Technologies

The three technologies remaining from the original nine which are acceptable for use as an advanced ECU are, in decreasing order of overall desirability, Stirling cycle heat pumps, thermoelectric heat pumps, and solid-vapor sorption heat pumps. In analyzing the performance of each of the three heat pumps, several tools were used. The principle measure of efficiency of a heat pump was evaluated using the coefficient of performance (COP), the ratio of the useful output to the power paid for. The COP is a dimensionless number, that is, the units of the numerator and denominator are the same and hence cancel. The COP for heating is different, and larger, than the COP for cooling. COP is the measure of performance most used by engineers world-wide, but in the US the heating industry in particular favors use of the energy efficiency ratio (EER), which measures the useful output in BTU per hour and the power paid for in watts. The COP and EER are related according to

$$\mathrm{EER} = 3.412\ \mathrm{COP}, \tag{1}$$

where the number 3.412 represents the conversion factor from watts to BTU per hour. The refrigeration industry has also adopted use of the EER, although refrigeration is sold in tons of cooling rather than BTU per hour. A ton of air cooling is 12,000 BTUs per hour, or 3.317 kilowatts.

Another feature of the analysis used in reviewing the performance of the various heat pumps is that in determining the COP account was taken of the efficiencies of the hot and cold heat exchangers. Often in analyzing a heat pump the COP is stated for given hot and cold heat exchanger temperatures. However, for different ambient conditions and the same heat exchanger temperatures the performance of the heat pump can change drastically. This is shown schematically in Figure 1. T_{cold} and T_{hot} are the temperatures from which heat is input and to which it is rejected (arrows show the direction of heat flow). T_{coldHX} and T_{hotHX} are the heat pump input and reject temperatures. Since heat must flow from a higher to a lower temperature, it must be that T_{cold} is greater than T_{coldHX} and T_{hotHX} is greater than T_{hot} for the heat flow to be in the right direction. This can be expressed in terms of the thermal resistances of the heat exchangers by

$$\Delta T_{cold} = T_{cold} - T_{coldHX} = R_{cold}\, Q_{cold} \tag{2}$$

and

$$\Delta T_{hot} = T_{hotHX} - T_{hot} = R_{hot}\, Q_{hot}, \tag{3}$$

where Q_{cold} and Q_{hot} are the rates of heat flow into and out of the heat pump and R_{cold} and R_{hot} are the thermal resistances of the cold and hot heat exchangers. A major component in designing a heat pump is to ensure that the heat exchanger thermal resistance is as small as possible for, as will be seen in the following discussions, increasing either ΔT will lower COP substantially.

COP is but one factor in evaluating a given heat pump technology, but it is an important one. Besides relating to energy consumption, it also affects weight and size, and impacts system complexity and complexity.

3.1.1 Stirling Cycle Heat Pumps.

The original concept of Stirling heat pump technology was introduced in the early nineteenth century, and Stirling devices were in general use until replaced by the Rankine cycle. Stirling heat pumps may be either thermally or mechanically driven. They typically use hydrogen, helium, nitrogen, or air as the working fluid. As with the acoustic heat pump, there are problems with leakages for the lower molecular weight gases, and a makeup source for the gas is often needed. No phase change of the gas takes place during the cycle as in the Rankine cycle. During a phase change, when a gas changes to a liquid or vice versa, large amounts of heat can be transferred at constant pressure. This heat transfer process is much simpler to achieve than the (ideally) isothermal compression/expansion processes of the Stirling cycle. Since the Stirling heat pump is a device with no internal combustion, sealing of the overall heat pump can easily be done. However leakage through the walls will still occur when lighter weight gases such as hydrogen and helium are used as the working fluid.

The Stirling cycle differs from more usual vapor-compression cycles in that regenerators (heat exchangers containing metal mesh or other heat storage means) are used to store heat in one portion of the cycle and release it later in the cycle, thereby enhancing the efficiency of the cycle. Since no combustion takes place internally and no exhaust is emitted the cycle is inherently environmentally clean.

Stirling heat pumps can be very quiet, since with proper linkages and balancing of the drive mechanism the forces on cylinder walls can be made small. Mechanically driven devices have higher noise levels than the thermally driven ones, and free piston devices can be still noisier, although that may be a result of them being in the early stage of their development. Pressures in the cylinders are high, and there are potential hazards to personnel if leaks occur. Temperatures are also high, again a hazard to personnel, providing a large thermal signature to enemy detectors, and a potential cause of fire if not properly shielded. Helium would be the most desirable refrigerant, as hydrogen, the candidate with the highest COP, is combustible and potentially explosive. None of the possible refrigerants are corrosive or toxic.

Substantial contributions to Stirling cycle technology were made during the 1930's through about 1980 by N. V. Philips of The Netherlands. Two of the Big Three auto makers (Ford and General Motors) have investigated the technology for use in automobiles, trucks, and buses. They are presently being considered for use in solar towers, to convert the intense heat focussed from collectors into electrical power. Otherwise, probably because of initial cost, in the US there presently does not appear to be much active work on developing them in the capacity range of interest for an ECU.

There have been several problems which have plagued development of the Stirling heat pump into an economically feasible heat pump. Seal leakages, wear, heat exchanger and regenerator efficiencies have all been problems which have required appreciable engineering effort to overcome. Along the way much engineering "art" has been developed. It has been said that "anyone" can build a Stirling device which works, but there are only a few teams in the world which have the resources and experience to develop a Stirling heat pump which approaches the highest state of this art.

Estimating size, weight, and cost of a Stirling ECU is difficult as there has been few Stirling heat pumps built and tested in the desired capacity. A rough estimate is that it would be of at least the size and weight of a large automobile engine. Cooling COPs as high as 2.5 at 35°C have been reported, and a hybrid 2 ton Stirling pulse tube heat pump currently being developed under contract with the Air Force has reported a COP of nearly 2. Development costs and time of designing, building, and testing prototypes would depend on the experience of the contractor. They likely would equal or exceed that of the thermoelectric and complex compound heat pumps because of the greater mechanical complexity.

3.1.2 Thermoelectric Heat Pumps.

Thermoelectric heat pumps are one of the most environmentally friendly of all the technologies considered. There is no gaseous or liquid refrigerant, hence no possibility for affecting the ozone or global warming. The absence of a refrigerant also means no hazard to personnel, no possibility of leakage, no elevated pressures, and no degradation of refrigerant over time. The heat pump is electrically powered, so there is no conversion of electricity to heat as in other technologies. The heat pump can be readily modulized so that it could be concentrated in areas where heat load is heaviest (e.g., near electronic equipment which generates heat or near concentrations of personnel). There are no elevated temperatures such as in heat activated devices, reducing hazards to personnel and also giving lower device heat signatures for infrared detection. Other than heat exchanger fans there are no moving parts, so noise and vibration are virtually absent and maintenance and wear are greatly reduced. Installation involves connection to the blower conduits and to the electric power source. No special alignment or level platform is needed. Since the systems are modular, repairs can be accomplished by replacement of plug-in modules. Except for the control unit and the power supply, a sealing enclosure of the working portion is unnecessary.

The principles governing thermoelectric heat pumps are not new, dating back well over a century. They work on the reverse principle of the thermocouple used in temperature measurement. In the temperature measurement role, heating the junction of two wires made of dissimilar metals results in a voltage difference across the junction which is proportional to the junction temperature. The heat pump operates on the reverse of this - applying a voltage results in heat being transferred at the junction. For the heat pump it is advantageous to use semiconductor materials instead of the wires. The particular semiconductor used depends on the temperature of the application. For temperatures at or near room temperature, properly doped bismuth telluride has the highest efficiency of materials found so far.

The semiconductor pairs are typically assembled in small modules. The larger heat pumping modules, capable of pumping 36 to 120 watts at a hot side temperature of 25 °C (77°F), are 40 to 60 millimeters (1.57 to 2.36 inches) on a side and 3.4 to 5 millimeters (0.134 to 0.197 inches) thick. From 3 to 254 pairs are typically used in a module, where they are sandwiched between metal plates. Electrically they are in series, but thermally they are in parallel. The number of semiconductor pairs and the length and cross-sectional area of each semiconductor leg determine the power capacity of the module. Stacking the semiconductors in only one layer restricts the module to a maximum temperature difference (T_{hotHX} - T_{coldHX}) of about 60°C (108°F), while going to 2 layers raises this to 105°C (189°F), and to 3, 125°C (225°F). Stacking the semiconductor pairs can thus raise the temperature lift of a module, but at a cost in COP (seen in Figure H.3). For the temperatures of interest for the ECU multi-layered modules have no advantage.

The heat exchangers used with thermoelectric devices are typically extruded aluminum fins, where with proper air flow thermal resistances as low as 0.02°C per watt. This allows ΔT_{cold} and ΔT_{hot} to be kept below 10°C (18°F). At higher ΔTs the COPs go to zero or in fact become negative - i.e., heating occurs at both ends of the device. The base surface of the heat exchangers must be milled to have a high degree of flatness to ensure good thermal contact with the modules.

There are two principal disadvantages to the use of thermoelectric heat pumps at this time. The first can be seen from Figure H.3, which shows that around 35°C (95°F) the COP decreases fairly rapidly when the ambient temperature is increased. Thus the heat exchanger temperature drops ΔT_{cold} and ΔT_{hot} will reduce the COP sharply from the ideal results. For example, if the ambient temperature is 35°C and the hot side heat exchanger temperature drop is 5°C, the system COP would be about 1.9 at a temperature of 40°C for the module compared with the ideal COP (no temperature drop at the heat exchanger) of about 2.6.

The second disadvantage is the number of modules needed. For cooling of 20 kilowatts (about 6 tons of cooling) the number of modules needed would be approximately 1,000. Module weight is in the half-ounce range, so the total module weight by itself would be approximately 35 to 40 pounds. If air-cooled extruded fin aluminum heat exchangers are used, sizes recommended (ITI-Ferrotec catalog) are in the neighborhood of 111 mm (4.38 inches) wide and 33 mm (0.37 inches) high, with lengths ranging from 150 mm (6 inches) to 305 mm (12 inches). Thus the weight of the heat exchangers would be at least fifty times the module weight, so an overall unit with these heat exchangers would be unlikely to meet the ECU weight requirements. The surface area of 1,000 modules would be about 40 square feet, and the heat exchangers would require an area of 182 square feet. More efficient heat exchangers are necessary to reduce weight and size.

The number of modules needed affects the costs considerably. Individual modules sell for anywhere from $16 to $43 each in lots of 1,000. Reduction in the costs of heat exchangers and modules would have to be an important part of the design of a thermoelectric ECU.

Thermoelectric refrigerators/heater are today sold in chain stores for use by travelers and campers. These units typically contain only one or two modules, and the maximum cooling capacity is of the order of 10 or so watts. Further, the manufacturers did not always realize the importance of proper heat exchanger design and placement of the air stream. Thus these units do not have sufficient power to do more than maintain the temperature of an already cooled object.

Several manufacturers provide small cooling units in the range of 350 watts for enclosure cooling. These use small fans to provide the air flow. Space vehicles such as the Challenger shuttle have used thermoelectric cooling with a water loop connecting the modules to a special undergarment worn by the pilot for cooling during reentry. Similar units have been developed for Army tank drivers. They are presently being tested for use in airport jetways and for cooling of parked airplanes. They have been used in France for cooling a railroad car and a submarine. Manufacturing of modules with 300 watt cooling capacity for use as building blocks are promised in two or three years time, and improved semiconductor materials showing higher efficiency also appears near.

Prototype units of an advanced level could be constructed with a minimum of engineering time and cost using presently available technology and experience by approximately a dozen manufacturers in this country. The experience of Marvel Corp. in France is available to US manufactures - Marvel is the company with the most experience with large capacity thermoelectric units. Jetway Inc. of Ogden Utah also is gaining experience with large capacity units.

3.1.3 Solid-Vapor Sorption Heat Pumps.

The use of solid-vapor absorption again is not a new technological principle. In the nineteenth century sufficient energy was stored in this manner to power a streetcar in Aachen Germany. Various gas-solid pairs have been used for absorption: ammonia adsorbed either in metal salts, carbon, or zeolites, and hydrogen adsorbed in metal hydrides are some of the more popular pairs. Most of these pairs have the problem that the gas is adsorbed primarily on the surface of the solid which acts to keep the gas from penetrating into the interior of the solid. Good mass and heat transfer are essential for adsorption heat pumps to have satisfactory efficiency and still meet size and weight requirements. The technology which presently appears to have the greatest proven capacity for energy storage per unit storage volume is the absorption of ammonia by a metal salt, termed a complex compound. The process is heat driven, with heat being given off during absorption and application of heat needed for desorption. The process is very much the same as vapor-compression with ammonia as the refrigerant, the difference being that the mechanical compressor in the vapor-compression process is replaced by a metal salt which plays the role of a chemical compressor. The process is not a continuous one, for when the absorption capacity of the salt is reached the process stops and the vessels containing the absorbing and desorbing salts have to be "interchanged" by means of valving before the process can continue. The devices can be completely sealed, with only heat exchanger loops entering and leaving.

The salts used as sorbing media are typically chlorides or bromides of metals such as sodium, strontium, barium, and the like. The salts are thus relatively cheap. As a rule of thumb, about 10 pounds of ammonia is needed for 3 tons of cooling. In the event of a severe leak in a system, approximately half of the ammonia would remain absorbed, so the amount of ammonia leaked during a breaching of the system would be small. Ammonia is lighter than air, so even in a severe leak the exposure of personnel to ammonia fumes would be limited and likely not fatal. In commercial refrigeration ammonia is the refrigerant most used because of its thermodynamic properties and its low price, and accident fatalities in the industry caused by ammonia fumes are rare. If a severe leak occurs and air enters the system, such an ECU would not be field reparable.

The principal disadvantage of this heat pump technology for use as an ECU are related to its being heat driven. For ECU purposes this heat would have to be provided by resistance heating. Typically, mean desorption temperatures are in the 300 to 400 °F range and pressures are around 225 psia. Such high pressures mean that the vessels containing the sorbant must be thick-walled and heavy, and will have a high thermal capacity. Much of the heat needed will go into heating the vessel, and most of that will be unrecoverable for cooling purposes. Cooling COPs were calculated as being between 0.6 to 0.7, although when losses due to heating of the vessel are taken into account more realistic COPs are 0.35 to 0.4. While achieving desorption by electrical resistance heating causes no major problems, the need for cooling to cause absorption does pose a problem. If a local cool water source is available there is no most convenient way of providing this cooling is. This is unlikely to be available in a Bare Base environment. The alternative which comes to mind is to use some of the cooling capacity of the heat pump to cool its absorbing salt and containing vessel, thereby decreasing the COP even more. Thus for ECU applications these devices are more appropriate to heating applications than to cooling ones. They do have the capacity for long-term energy storage (such as were used in the Aachen streetcars) and it is possible that a system could be arranged with more than two vessels so that more heat could be recovered and the operation made more continuous. However, that would lead to increased size, weight, and complexity.

Ammonia does attack copper, brass, some plastics, and some sealing and gasketing materials.

An additional potential disadvantage of this technology is the possibility of non-condensible gases developing within the system during either operation or storage. During the cycle, ammonia is first condensed and then evaporated. If there are contaminant trace gases present, they may not condense, affecting the partial pressures and the condensibility of the ammonia, perhaps to the degree that the cycle is shut down. Non-condensibles can arise due to impurities in commercial ammonia, or may be introduced by the sorbing salts or from contaminants introduced by the heat pump metal, manufacturing process, or filling process. Long term storage could be a problem for this reason. Care in the initial construction and filling can reduce them initially, but to ensure that no non-condensibles develop during operation requires care that internal pressure never goes below atmospheric and that any refilling of refrigerant needed during storage is properly done.

Present applications of this technology are few. The technology is used to store ammonia during repair of vapor-compressor ammonia systems, allowing for recovery of the ammonia with no or minimal release of ammonia to the atmosphere. Use of the technology for quick cooling of beverages and cooling of ice cream sold by vendors in ball parks and on the street apparently is nearing the marketplace. At least in the US, other modern applications seem to not have gained much attention.

To date there have been few prototypes built of even 3 ton cooling capacity, and there are no reported performance results. Accelerated tests have been conducted as to the repeatability of the sorption process over many cycles with good results, with sorption rates actually increasing during the first 500 cycles. However this does not test the long-term effect of the sorbing media and the ammonia being in contact with the vessel and associated plumbing. It is likely that several prototypes would have to be built and tested, the results of one test results being used to aid in the design of the next prototype. The stability of the unit under long term storage, and the susceptibility of media to damage during transport would also have to be investigated, as the media is mounted on heat exchangers in a crystalline form.

Costs of development of the first usable ECU would likely be higher than for the thermoelectric heat pump by several orders of magnitude. Size and weight would also be larger, and vehicle transport including lifting devices would be necessary to move the device to a site and then install it. It is unlikely that one man working alone could install this ECU, two to four being a more reasonable number.

3.2 Comparison of Efficiencies of Acceptable Technologies.
Cooling COPs for the three acceptable technologies are shown in Figures 2 through 6, and heating COPs are shown in Figures 7 through 9. Figure 2 compares the cooling COPs for a ΔT (the difference between the cold temperature and the cold heat exchanger temperature) of zero. Vapor compression devices with either R-11 or R-22 give much higher COPs over the entire temperature range of 35-46°C (95-115°F) than the three alternate technologies. In this plot the Stirling heat pump is modeled both with and without the regenerator pressure drop, to show the appreciable effect of this pressure drop on performance. The no pressure drop results are of course an idealized model, and is only included to show the pronounced effect that the losses can have on the performance. For this ΔT the thermoelectric heat pump has the highest COP over most of the range, followed by the Stirling and then the complex compound (solid-vapor) absorption results. All of the curves are fairly flat except for the thermoelectric heat pump, whose COP drops by a factor of about two over the 11°C range. The thermoelectric results include all of the losses which can occur. As explained earlier, the complex compound results are decreased by a factor of approximately two when unrecoverable heat losses from the vessels are included. Complex compound heat pumps are thermally driven, which has the effect of lowering their COPs by approximately one-third compared to a mechanically driven heat pump.

Figure 3 shows similar results but with ΔT equal to 5°C (9°F). The ranking this time has the Stirling heat pump first, followed by thermoelectric and then complex compound absorption. Figures 4, 5, and 6 have ΔTs of 10, 15, and 20°C, respectively. The ranking in all cases shown in these three figures is Stirling and complex compound absorption - thermoelectric COP has gone to zero for ΔTs greater than about 7°C (12.5°F)! This possibility was noted above, and illustrates the need for proper heat exchanger design to ensure a very low thermal resistance.

Heating COPs are shown in Figures 7 through 9, with ΔTs of 0, 5, and 10°C. Ambient temperatures of 0 to -30°C (32 to -22°F) are shown. The idealized Stirling heat pump with no regenerator pressure drop is shown along with the thermoelectric and complex compound absorption, with the relative ranking in that order in all cases. As the ambient temperature goes lower, the COP of the thermoelectric device is seen to approach unity, signifying that the device is operating almost as pure resistance heating.

In all of these results the model used for the thermoelectric heat pump was a single stage model. The reason for the decrease in cooling COP as ΔT is increased was pointed out in the discussion above - a single stage thermoelectric module can maintain at most a temperature difference across it of about 60°C. As that value of temperature difference is reached the COP drops precipitously. Staged modules would allow greater ΔTs, but would be more difficult to switch between heating and cooling modes.

3.3 Hazards, Tradeoffs, and Risks Analysis.

The risks and hazards involved in each technology are classifiable as risks and hazards to personnel, risk of not meeting size, weight, and assembly requirements, risks involved in storage of the units, risks involved in reliability of the technology, operation and repair complexity, risks and costs involved in realizing the technology, manufacturing and operating costs. These can be summarized in the following list:

A. Environmental compliance requirements.
   1. Refrigerant hazards to environment.
      a. Ozone depletion potential (ODP).
      b. Global warming potential (GWP).
   2. Refrigerant hazards to personnel.
      a. Toxicity.
      b. Flammability.
      c. Elevated pressure hazards.
      d. Elevated temperature hazards.

B. Logistics requirements.
   1. Size and weight of the ECUs.
   2. Potential startup problems after long storage or use.
      a. Reaction between refrigerant and outer casing.
      b. Deterioration of seals/ leakage of refrigerant.
      c. Generation of non-condensible gases.
      d. Compressor/engine reliability.
      e. Ease of being able to diagnose/repair problems.
   3. Complexity of the ECU system.
      a. Mechanical complexity.
      b. Control system complexity.
   4. Reliability.
      a. Reliability of individual components.
      b. Reliability of the total system.
      c. Need to recharge refrigerants.
   5. Ease of assembly of the units
   6. Repairability in the field.
   7. Ease of operation of the system - possibilities of operator/setup errors.

C. Operational requirements.
   2. Signatures presented to enemy detectors

a. Heat
b. Acoustic
c. Noise and vibration.

D. Manufacturing and cost requirements.
1. State of development of the technology
a. Amount of R&D necessary for a working model.
b. Likelihood of a successful working model in 3 to 5 years
2. Costs
a. Initial cost estimate of R&D
b. Manufacturing costs in small lots
c. Operating cost efficiencies.

A tabular summary of an assessment of the three technologies involving thermoelectric, complex compound, and Stirling heat pumps is shown in Tables 1 through 3.

To assess a numerical score to the analysis, an attribute scoring grade of 1 to 5 was given to each item. While this is a coarse grading scheme, it is reasonable for rating a concept where the actual design would require considerable engineering and their is considerable uncertainty as to how closely goals will be reached. The scoring was as follows:

1 - no, no possibility of success
2 - not likely
3 - moderate, uncertain, average
4 - good, above average, close to goal
5 - best, goal reached, acceptability unquestionable

A high score for an item thus represents a desirable attribute of that item, a low score an undesirable attribute. Since no prototypes have been built for any of these technologies, the above scores are necessarily "educated guesses". It is believed however that the relative scoring gives a good representation and comparison of the three technologies.

Attribute weights were provided by Tyndall AFB personnel. The weighted totals show Stirling heat pumps and thermoelectric heat pumps to be very close in scoring, and both to be superior to complex compound heat pumps. It is unlikely that either technology will achieve the cooling COP goal of 3, although with existing state of the art the Stirling technology will have the higher COPs for temperatures above the 95 °F level. As discussed in the next section, efficient heat exchanger design is crucial to the performance of any of these technologies. Presently Stirling technology has the greater experience at the energy levels required for an ECU. This is a very important issue which favors Stirling at this time.

Table 1. Technical Evaluation Form - Stirling Technology.

	Attribute Weight X	Attribute Performance =	Attribute Score
ENVIRONMENTAL COMPLIANCE REQUIREMENTS			
1. The final prototype unit will use zero ODP materials	5	5	25
2. The final prototype unit will use low GWP or materials *	4	5	20
3. The final prototype unit will use non-flammable materials	4	5	20
4. The final prototype unit will use non toxic materials (NOAEL > 2%)**	4	5	20
* Atmospheric life of 35 years or less ** No observable adverse effects level, 2% concentration in open air from uncontrolled release		*subtotal*	*85*
LOGISTICS REQUIREMENTS			
1. The final prototype unit will achieve 150 lbs total unit weight per 12 KBTUs of cooling	3	3	9
2. The final prototype unit will achieve 5 ft^3 total unit volume per 12 KBTUs of	3	3	9
cooling	3	4	12
3. The final prototype unit will have a shelf life of at least 15 years	3	3	9
4. The final prototype unit will be more durable than comparable R-22 units	3	2	6
5. The final prototype unit will be more reliable than comparable R-22 units			
6. The final prototype unit will require less support logistics, have fewer moving parts	3	3	9
7. Working fluids and refrigerants will not require recharge intervals of less than 3 years	3	3	9
		subtotal	*63*
OPERATIONAL REQUIREMENTS			
1. The final prototype unit will provide 12 KBtu of cooling and maintain a COP of 3 or better at 95 F.	3	4	12
2. The final prototype unit will provide 12 KBtu of heating and maintain a COP of 3 or better at 47 F.	3	4	12
3. The final prototype unit will be operable between 25 F-125 F in the presence of 0 -100% RH	3	4	12
4. The final prototype unit will be operable from 3 ϕ 220 VAC 60 hz	4	5	20
5. The final prototype unit will produce less noise than comparable R-22 units	3	3	9
6. The final prototype unit will produce less IR signature than comparable R-22 units	3	3	9
7. The final prototype unit will provide positive pressure with respect to ambient within the conditioned airflow circuit to reduce chem/bio infiltration	3	5	15
8. The final prototype unit will be resistive to deterioration.	3	3	9
		subtotal	*98*
MANUFACTURING AND COST REQUIREMENTS			
1. The final prototype unit will reduce overall replacement and O&M costs	2	3	6
2. The technology can be cost effectively manufactured	3	2	6
		subtotal	*12*
		TOTAL	**258**

Table 2. Technical Evaluation Form - Thermoelectric Technology.

	Attribute Weight X	Attribute Performance =	Attribute Score
ENVIRONMENTAL COMPLIANCE REQUIREMENTS			
1. The final prototype unit will use zero ODP materials	5	5	25
2. The final prototype unit will use low GWP or materials *	4	5	20
3. The final prototype unit will use non-flammable materials	4	5	20
4. The final prototype unit will use non toxic materials (NOAEL > 2%)**	4	5	20
* Atmospheric life of 35 years or less ** No observable adverse effects level, 2% concentration in open air from uncontrolled release		*subtotal*	*85*
LOGISTICS REQUIREMENTS			
1. The final prototype unit will achieve 150 lbs total unit weight per 12 KBtu of cooling	3	2	6
2. The final prototype unit will achieve 5 ft^3 total unit volume per 12 KBtu of cooling	3	1	3
3. The final prototype unit will have a shelf life of at least 15 years	3	4	12
4. The final prototype unit will be more durable than comparable R-22 units	3	3	9
5. The final prototype unit will be more reliable than comparable R-22 units	3	2	6
6. The final prototype unit will require less support logistics, have fewer moving parts	3	4	12
7. Working fluids and refrigerants will not require recharge intervals of less than 3 years	3	5	15
		subtotal	*63*
OPERATIONAL REQUIREMENTS			
1. The final prototype unit will provide 12 KBtu of cooling and maintain a COP of 3 or better at 95 F.	3	2	6
2. The final prototype unit will provide 12 KBtu of heating and maintain a COP of 3 or better at 47 F.	3	2	6
3. The final prototype unit will be operable between 25 F-125 F in the presence of 0 -100% RH	3	3	9
4. The final prototype unit will be operable from 3 ϕ 220 VAC 60 hz	4	5	20
5. The final prototype unit will produce less noise than comparable R-22 units	3	5	15
6. The final prototype unit will produce less IR signature than comparable R-22 units	3	5	15
7. The final prototype unit will provide positive pressure with respect to ambient within the conditioned airflow circuit to reduce chem/bio infiltration	3	5	15
8. The final prototype unit will be resistive to deterioration.	3	4	12
		subtotal	*98*
MANUFACTURING AND COST REQUIREMENTS			
1. The final prototype unit will reduce overall replacement and O&M costs	2	2	4
2. The technology can be cost effectively manufactured	3	2	6
		subtotal	*10*
		TOTAL	**254**

Table 3. Technical Evaluation Form - Complex Compound Technology.

	Attribute Weight X	Attribute Performance =	Attribute Score
ENVIRONMENTAL COMPLIANCE REQUIREMENTS			
1. The final prototype unit will use zero ODP materials	5	5	25
2. The final prototype unit will use low GWP or materials *	4	5	20
3. The final prototype unit will use non-flammable materials	4	5	20
4. The final prototype unit will use non toxic materials (NOAEL > 2%)**	4	1	4
* Atmospheric life of 35 years or less ** No observable adverse effects level, 2% concentration in open air from uncontrolled release		*subtotal*	*69*
LOGISTICS REQUIREMENTS			
1. The final prototype unit will achieve 150 lbs total unit weight per 12 KBtu of cooling	3	1	3
2. The final prototype unit will achieve 5 ft^3 total unit volume per 12 KBtu of cooling	3	1	3
3. The final prototype unit will have a shelf life of at least 15 years	3	3	9
4. The final prototype unit will be more durable than comparable R-22 units	3	3	9
5. The final prototype unit will be more reliable than comparable R-22 units	3	2	6
6. The final prototype unit will require less support logistics, have fewer moving parts	3	5	15
7. Working fluids and refrigerants will not require recharge intervals of less than 3 years	3	3	9
		subtotal	*54*
OPERATIONAL REQUIREMENTS			
1. The final prototype unit will provide 12 KBtu of cooling and maintain a COP of 3 or better at 95 F.	3	1	3
2. The final prototype unit will provide 12 KBtu of heating and maintain a COP of 3 or better at 47 F.	3	1	3
3. The final prototype unit will be operable between 25 F-125 F in the presence of 0 -100% RH	3	4	12
4. The final prototype unit will be operable from 3 ϕ 220 VAC 60 hz	4	5	20
5. The final prototype unit will produce less noise than comparable R-22 units	3	5	15
6. The final prototype unit will produce less IR signature than comparable R-22 units	3	1	3
7. The final prototype unit will provide positive pressure with respect to ambient within the conditioned airflow circuit to reduce chem/bio infiltration	3	5	15
8. The final prototype unit will be resistive to deterioration.	3	3	9
		subtotal	*80*
MANUFACTURING AND COST REQUIREMENTS			
1. The final prototype unit will reduce overall replacement and O&M costs	2	3	6
2. The technology can be cost effectively manufactured	3	3	9
		subtotal	*15*
		TOTAL	**218**

3.4 Conceptual Designs and Considerations.

3.4.1 Stirling Heat Pump Design.

A Stirling heat pump can be powered either by a Stirling engine or a motor. Since electric power is the power source available for the bare base ECU, an electric powered motor is the engine of choice. While hydrogen is the gas which would provide the highest efficiency, its flammabiliity and explosion potential means that helium would be the preferred gas for an ECU at a small cost in efficiency.

There are a number of design choices to be made by the engineer. Compressor, heat exchangers, and regenerator design choices are to be selected. Problems to be overcome include the following:

- Metals appear porous to low molecular weight gases. The low molecular weight of helium means that it may be necessary to plate all interior surfaces to ensure that losses of gas through the relatively porous walls are minimal. Also care must be taken at all seals to reduce potential sources of leakage. Provision of a makeup gas source is necessary.
- Wearing of surfaces in the compressor, particularly between the piston and cylinder, has been a perennial problem for Stirling devices which has not been fully solved at this time. Wear can be reduced by using a mechanical drive (e.g., the rhombic drive) which greatly reduces side loading on the piston.
- Sealing between the piston and cylinder wall has also been a problem with Stirling technology. The pressure difference across the wall can be high, and the seal must be able to withstand reversal of direction. Temperatures and pressures in a Stirling refrigerator are not as high as in a Stirling engine, but any degradation of the seal which would allow gases to bypass the seal will affect efficiency.
- Design of efficient, compact heat exchangers has been a further difficulty. In particular the pressure drop across the regenerator has a strongly adverse effect on overall efficiency. Design of a regenerator with low pressure drop, yet high heat capacity and a quick thermal response, has been another strong challenge to the Stirling engineer. One solution which has been tried is the use of large frontal area regenerators, to reduce porosity. This unfortunately is accomplished at the cost of compactness.

These problem areas have all required "new art" and innovative technology which for the most part has been kept proprietary.

The best cooling COPs which have apparently been obtained to date for Stirling refrigeration are around the 2.5-2.6 range for an ambient rejection temperature of 95°F (35°C).

3.4.2 Thermoelectric Heat Pump Design.

The design of a thermoelectric heat pump is very flexible, and could easily be varied as the design of the portable shelter changes. For instance, if rigid or semi-rigid walls are used in future portable shelters, cooling and heating could be accomplished by a number of low power units distributed around the shelter, mounted in holes in the walls.

As an example of sizing and the use of modular cooling, ThermoElectric Cooling America Corporation (teca) offers a 1,500 BTU per hour cooling, 1,360 BTU per hour heating unit (440 watts cooling, 400 watts heating) which is off-the-shelf and fits in an opening about 17.25 inches by 8.75 inches. Overall dimensions of the unit are 18 inches by 12.65 inches by 9.69 inches, with a weight of 46 pounds. The units could be easily installed by dropping them into openings in the walls, attaching a dozen or so screws, and plugging into a 115 or 230 VAC outlet. These units are designed for harsh industrial environments such as NEMA-4X, and are claimed to withstand corrosive salt spray, shock, vibration, wind-blown dust, rain, and water hose-down. Mounting in any orientation is possible, the units withstand shock, vibration, and corrosive environments, and have low vibration, low noise, and low maintenance. Small fans are provided on the exterior side, and performance likely could be improved by the installation of similar fans on the inside. In case of contamination, the outside cover could be removed by taking out several screws and the heat exchanger then scrubbed down with a brush or hose. The electrical control and distribution part of the heat pump is on the inside of the shelter and is sealed, so no decontamination would be necessary there. No outside air is transported through the unit described above, so exchange air would be introduced through shelter leaks or filtered openings in the sheltered wall. This would reduce the possible need to decontaminate the interior of the shelter. To provide 5 tons of cooling (60,000 BTUs per hour), 40 such units would be needed. Single unit pricing for these units was $1,750 in 1993.

The above should be understood to not be a recommendation for this particular manufacturer or these particular units, but rather to point out what is available on the over-the-counter market. Other manufacturers provide similar units, and all manufacturers are willing to design modules of special sizes and configurations for an end user.

The off-the-shelf units which are listed in catalogs all appear to accomplish heat transfer by having small fans blow air perpendicular to heat exchanger fins. As pointed out, the volume and weight of the heat exchangers needed for the power levels of an ECU is unacceptable. A circulating liquid heat transfer loop likely is needed to reduce the volume and weight of the heat exchangers to acceptable levels.

The greatest challenge facing the designer of a thermoelectric heat pump is the large number of modules needed, likely more than a thousand, and the efficient transfer of heat from them. Present modules based on bismuth telluride have low heat pumping per module, albeit the heat pumped per volume is high compared to technologies such as thermoacoustic The need for efficient heat exchangers has been recognized only recently in the thermoelectric industry, and the efficient heat transfer at high power levels has not been sufficiently addressed. The industry is starting to look at this along with the possibility of employing materials with higher figures of merit in the room temperature range, but so far only brute force methods have been applied at the sacrifice of economy.

3.4.3 Complex Compound Heat Pump Design.

The design of a complex compound heat pump consists of sizing of the evaporator and condenser, design of the pressure vessel containers and support heat exchangers for the complex compound salts, and selection of valving for interchanging of the two vessels. Each of these poses separate problems.

Sizing of the evaporator and condenser is straightforward, but availability of off-the-shelf heat exchangers in the 5 to 15 ton range which are compatible with ammonia is not favorable. In this range most manufacturers provide steel units which are not compatible with ammonia. Copper or aluminum would be the material of choice, and the ammonia heat exchanger industry generally manufactures these in sizes starting at 50 to 100 tons. Thus a conventional heat exchanger analysis would have to be performed and then a manufacturing methodology developed. Since it would be most convenient for the ECU to have an air-cooled heat exchanger, finned tube or plate-fin heat exchangers are obvious choices. The evaporator would be designed to operate near atmospheric pressure and could be thin walled. The condenser would operate near 15 bars internal pressure (approximately 220 psia) and would require thicker walls. In both cases the fins would be attached to the tubes by expansion of the tube diameter, either by pressurization of the tube or forcing a ball or similar object through it. No new technology is needed for this process.

One way spring operated check valves are obvious choices for passive operation of the valving, but careful attention would have to be paid to their selection to insure reliable operation. It may be necessary to use electrically operated valves with external active control to ensure reliability.

The primary design challenge for this heat pump is the two identical pressure vessels. The metal salt has to be supported in such a manner to ensure a good thermal contact with the heat exchanger fluid and good contact with the ammonia flow. This should be accomplished within a vessel capable of withstanding the pressure and which is yet compact. The suggestion is to support the salt directly on finned heat exchangers, keeping the salt in place with porous media in contact with ammonia-containing passages. The weight of the vessel should be kept to an absolute minimum since in a cooling situation heating of the vessel is an unrecoverable cost which can reduce the cooling COP by as much as 50%. For heating applications some of this heat can be recovered, at the possible price of an additional heat transfer loop.

At any given time one pressure vessel is being heated and the other cooled, so simultaneous heating/cooling fluid must be supplied. A possibility is an electric boiler to provide superheated steam for heating purposes and a water cooling loop for cooling. Switching of the vessels between their heating and cooling roles would be accomplished by active control of solenoid valves. A supply of treated water, preferable deionized, for the boiler would be necessary to keep down corrosion and reduction of thermal efficiency of the various heat exchanger surfaces.

Much of the technology involved in providing suitable heat and mass transfer to the metal salts is proprietary and is not discussed in the open literature. It appears that at this time no superior solutions to these heat and mass transfer problems have been solved. As mentioned previously, since this technology is heat driven the need to have the ECU electrically driven results in a loss of apparent efficiency compared to technologies which are electrically based. Maintenance of boilers and the need for good water supplies limit the applicability of this technology further. Since the ideal cooling COP of this absorption technology is less than 0.7 for a single stage heat pump, even with the best design the conversion of heat to electricity and back to heat lowers the overall COP to the point where this technology does not appear suitable to Air Force Bare Base ECU needs.

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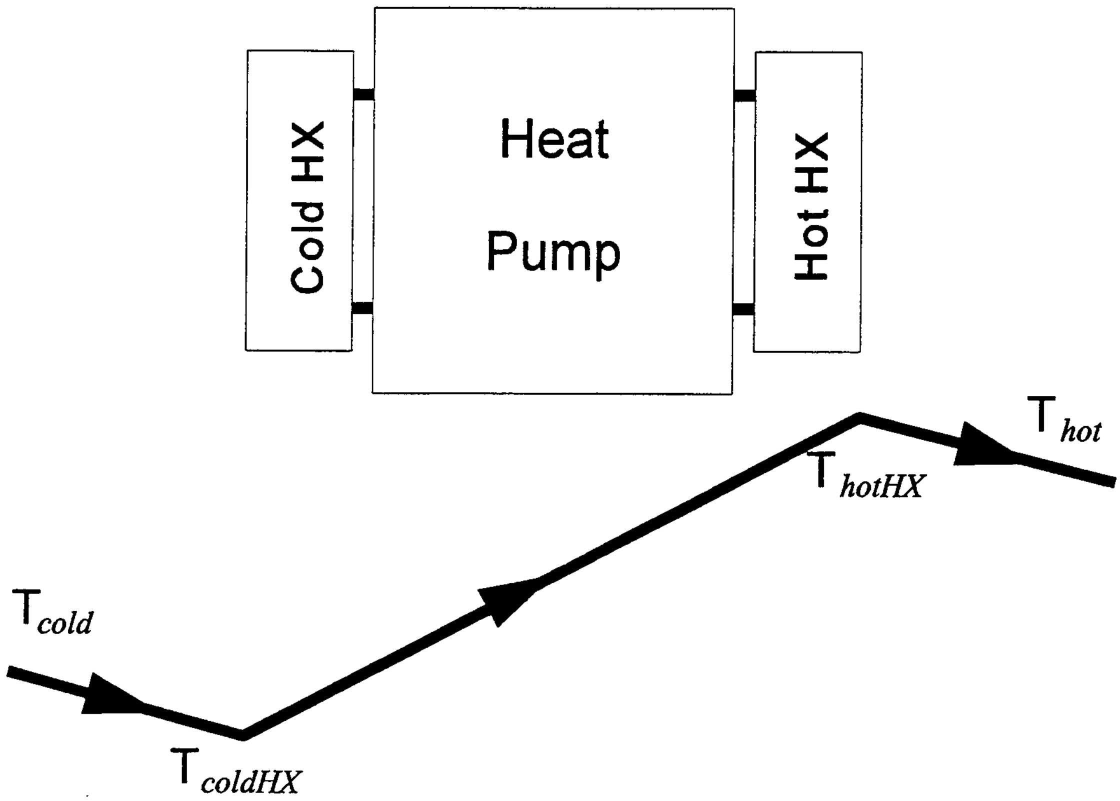

Figure 1. Schematic of temperatures affecting heat flow in a heat pump.

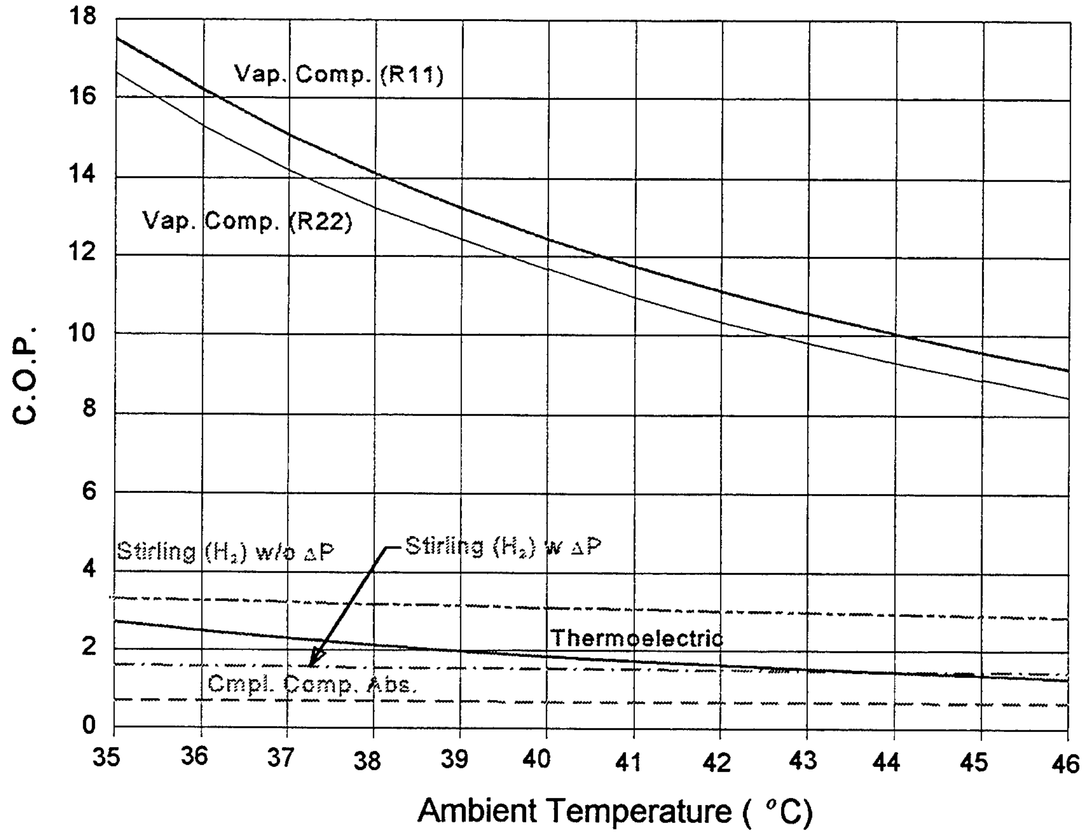

Figure 2. Cooling COPs for $\Delta T = 0$.

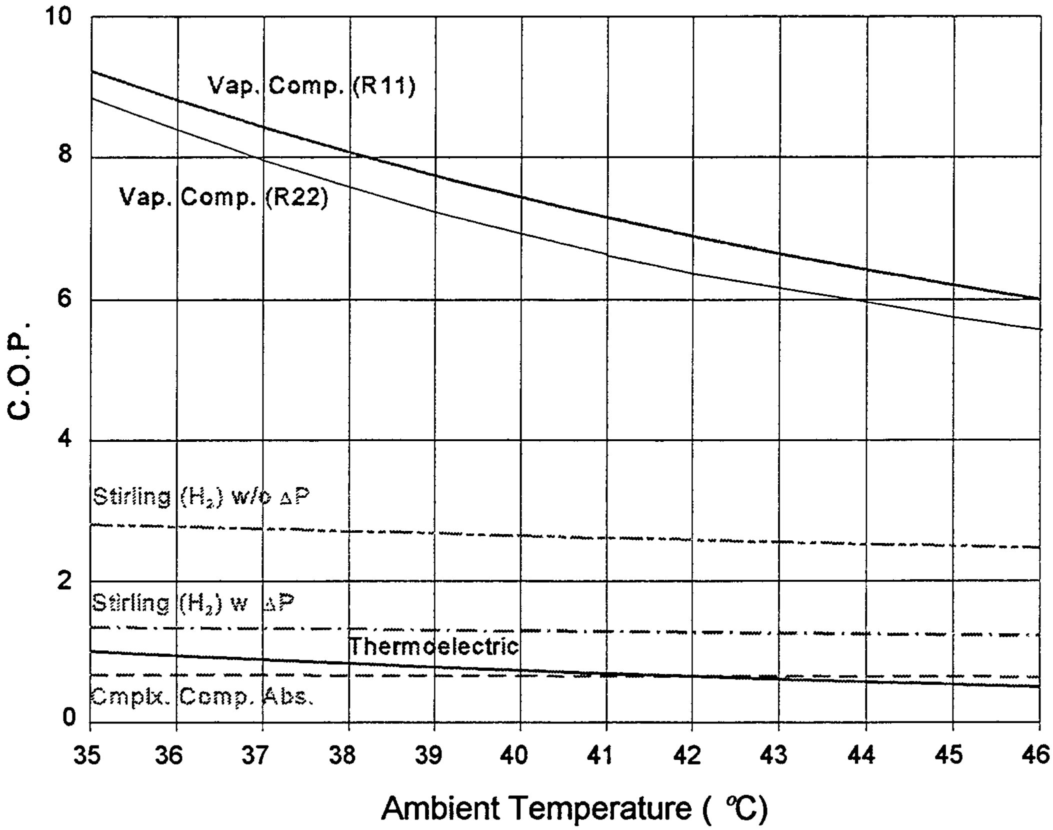

Figure 3. Cooling COP for $\Delta T = 5°C$.

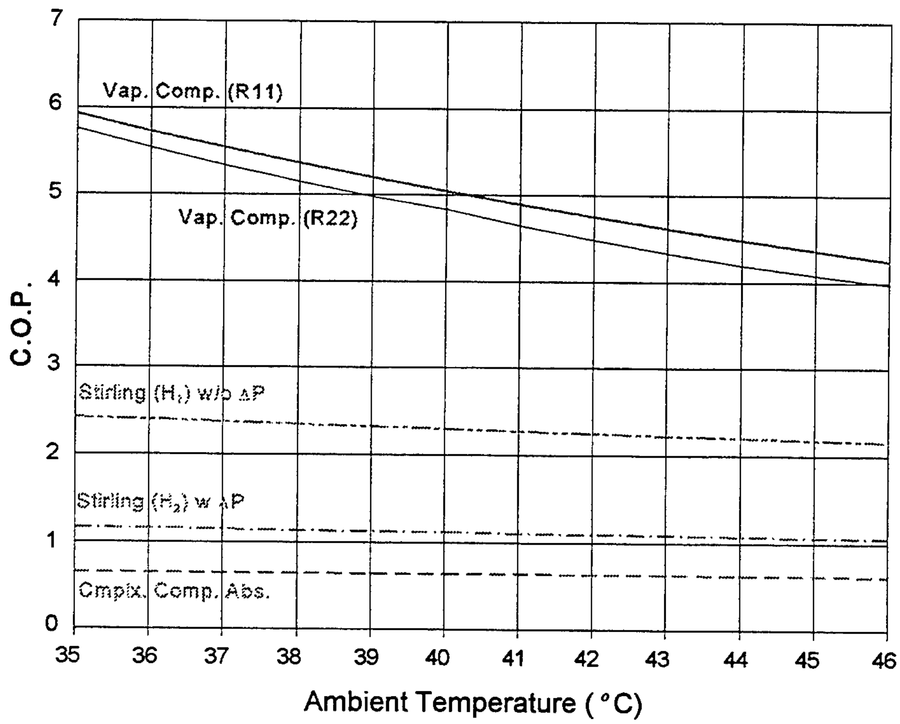

Figure 4. Cooling COP for ΔT = 10°C.

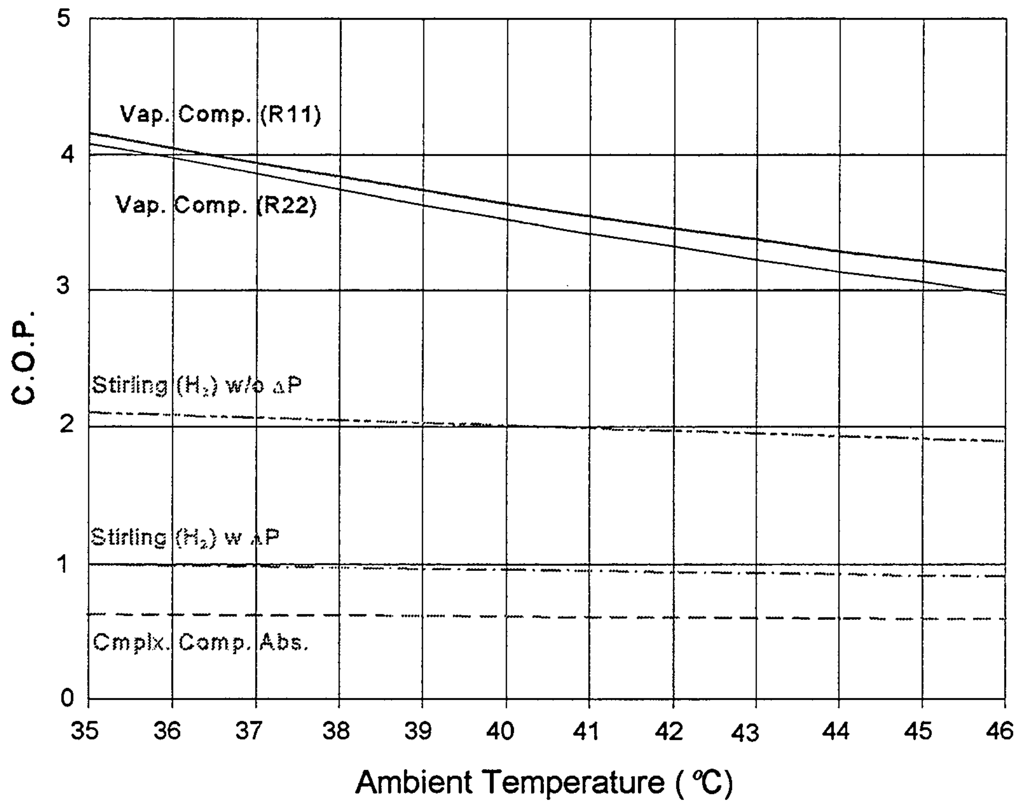

Figure 5. Cooling COP for ΔT = 15°C.

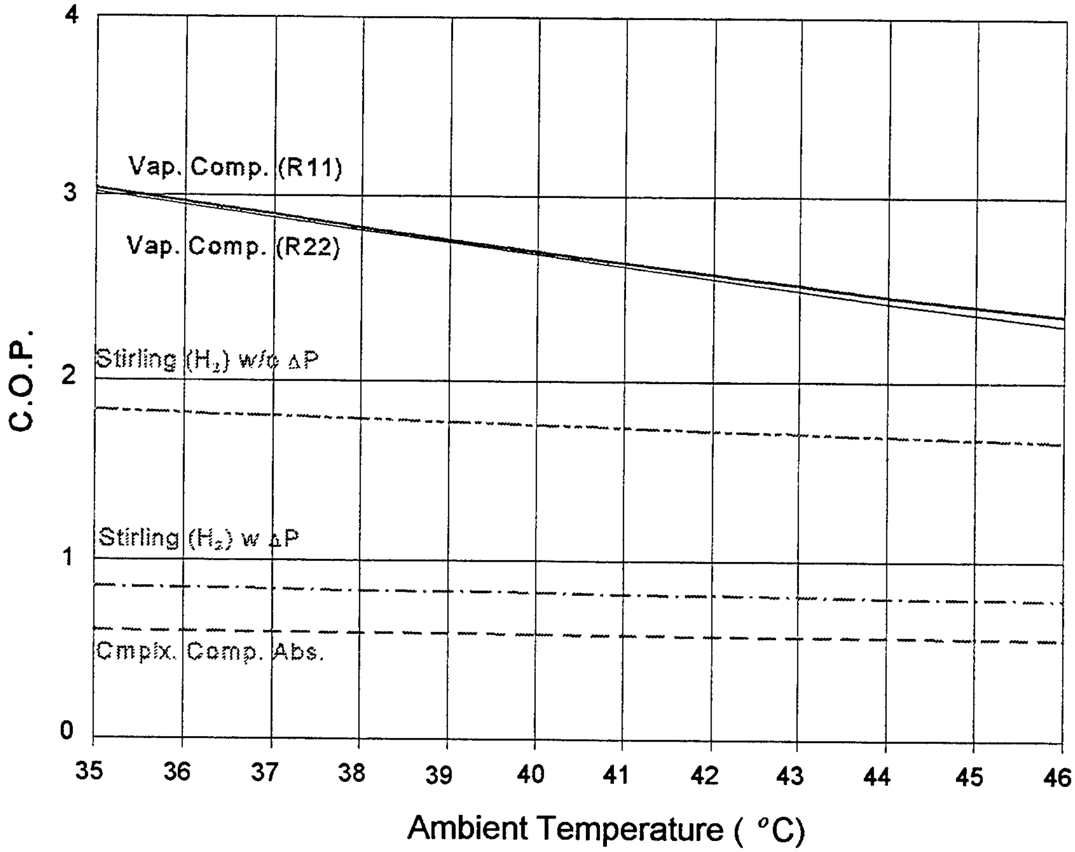

Figure 6. Cooling COP for ΔT = 20°C.

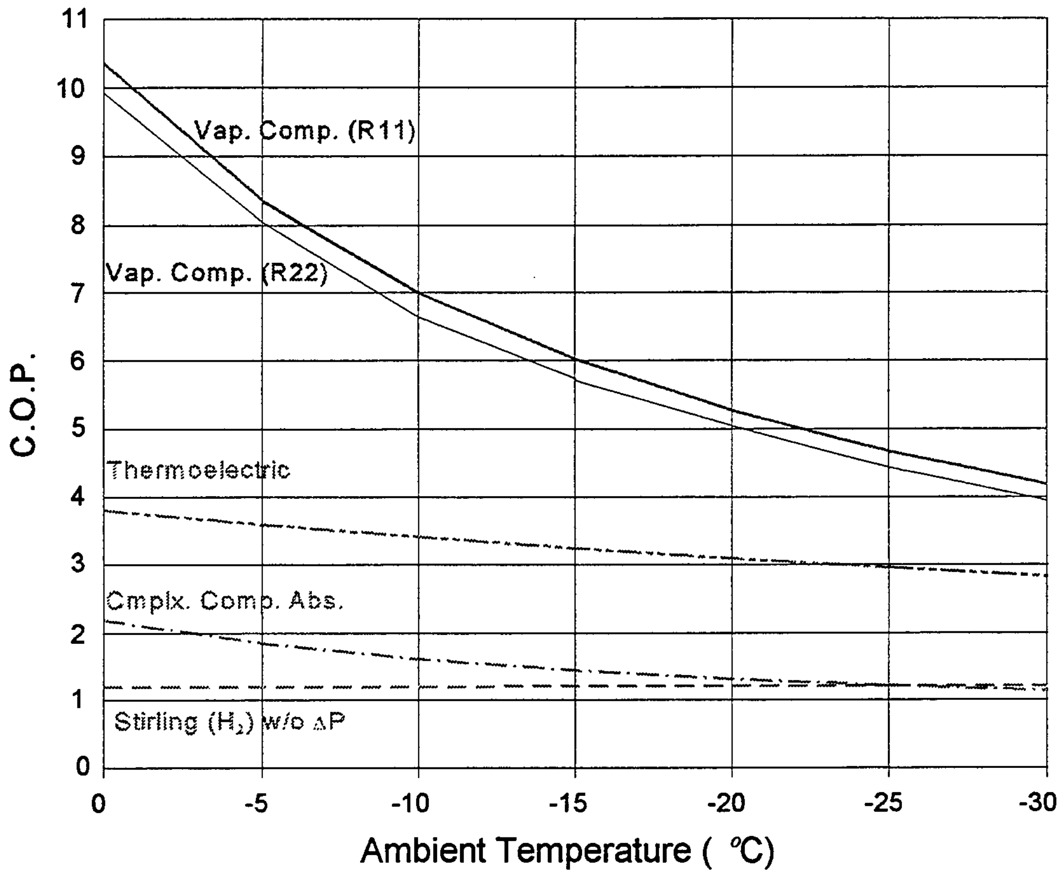

Figure 7. Heating COP for $\Delta T = 0$.

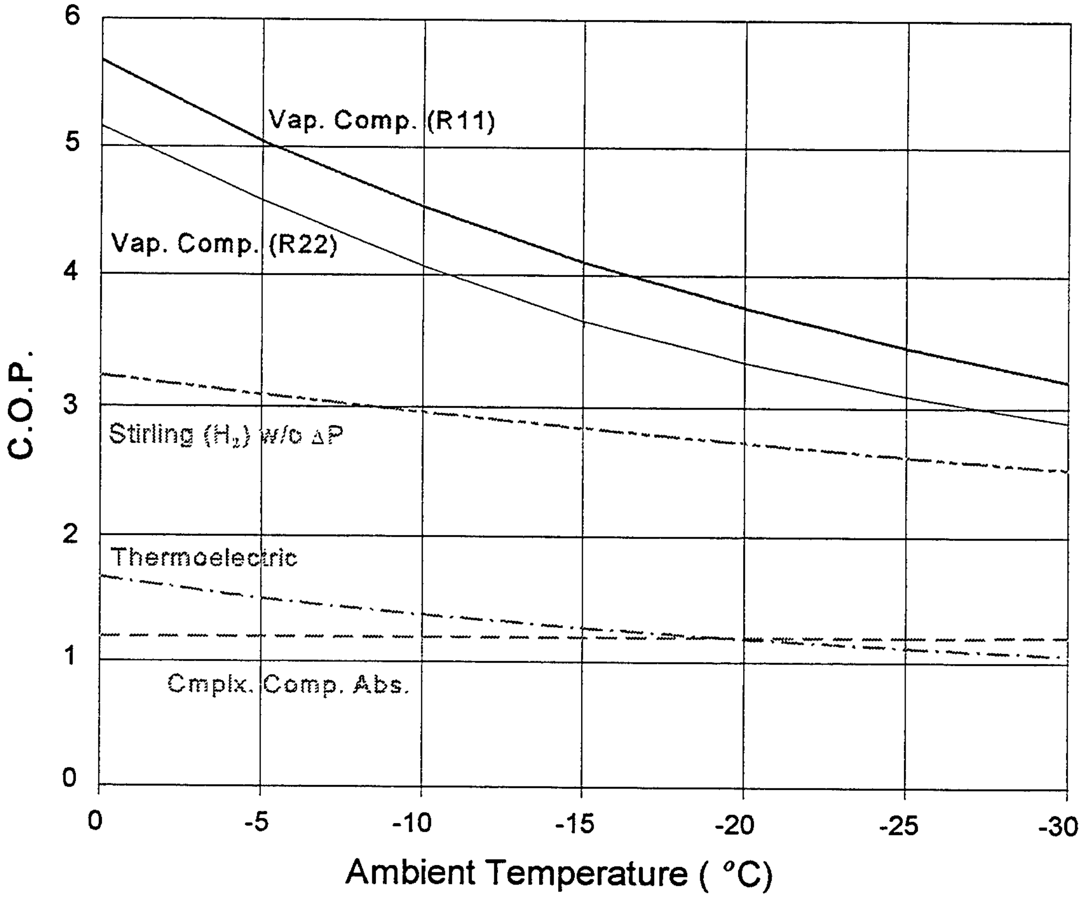

Figure 8. Heating COP for ΔT = 10°C.

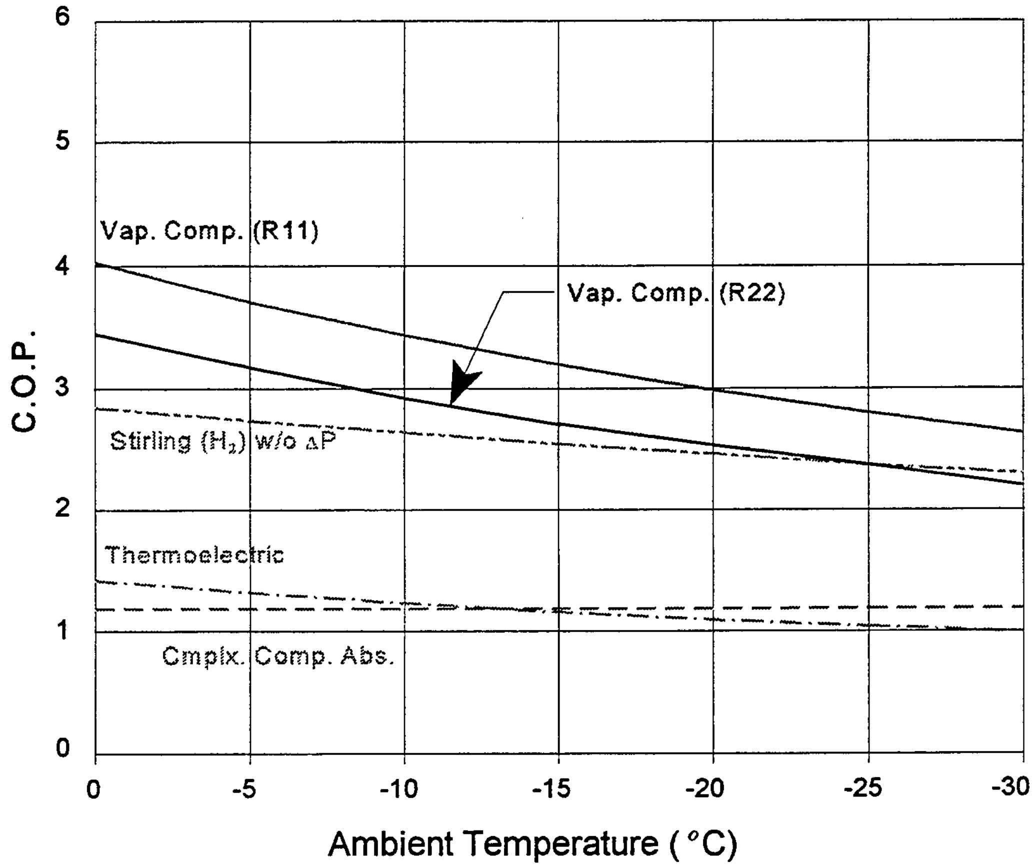

Figure 9. Heating COP for ΔT = 20°C.